Renewable and Sustainable Energy Reviews 13 (2009) 2245–2262

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of renewable energy technologies integrated with desalination systems

Mohamed A. Eltawil [a,b,*], Zhao Zhengming [a], Liqiang Yuan [a]

[a] The State Key Laboratory of Power System, Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China
[b] Agricultural Engineering Department, Kafrelsheikh University, box 33516, Egypt

ARTICLE INFO

Article history:
Received 25 September 2008
Received in revised form 6 March 2009
Accepted 10 June 2009

Keywords:
Renewable energy
Water sources
Desalination technologies
Reverse osmosis
Economics

ABSTRACT

Energy is an essential ingredient of socio-economic development and economic growth. Renewable energy provides a variable and environmental friendly option and national energy security at a time when decreasing global reserves of fossil fuels threatens the long-term sustainability of global economy. The integration of renewable resources in desalination and water purification is becoming increasingly attractive. This is justified by the fact that areas of fresh water shortages have plenty of solar energy and these technologies have low operating and maintenance costs. In this paper an attempt has been made to present a review, in brief, work of the highlights that have been achieved during the recent years worldwide and the state-of-the-art for most important efforts in the field of desalination by renewable energies, with emphasis on technologies and economics. The review also includes water sources, demand, availability of potable water and purification methods. The classification of distillation units has been done on the basis of literature survey till today. A comparative study between different renewable energy technologies powered desalination systems as well as economics have been done. The real problem in these technologies is the optimum economic design and evaluation of the combined plants in order to be economically viable for remote or arid regions. Wind energy technology is cheaper than the conventional ones, and used extensively around the world. The slow implementation of renewable energy projects especially in the developing countries are mostly due to the governments subsides of conventional fuels products and electricity. The economic analyses carried out so far have not been able to provide a strong basis for comparing economic viability of each desalination technology. The economic performances expressed in terms of cost of water production have been based on different system capacity, system energy source, system component, and water source. These differences make it difficult, if not impossible, to assess the economic performance of a particular technology and compare it with others. Reverse osmosis is becoming the technology of choice with continued advances being made to reduce the total energy consumption and lower the cost of water produced.

Contents

* Corresponding author at: The State Key Laboratory of Power System, Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China. Tel.: +86 10 62773237; fax: +86 10 6279415.
E-mail address: eltawil69@yahoo.co.in (M.A. Eltawil).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2009.06.011

1. Introduction

Water has been recognized as a basic human right. Large quantities of fresh water are required in many parts of the world for agricultural, industrial and domestic uses. As of today, nearly one fourth of mankind is suffering from inadequate fresh water supply [1]. Owing to the foreseen growth of population worldwide (especially in the developing countries), the above mentioned situation will be more and more critical over the next two decades or so.

Drought and desertification are increasing significantly, involving wider and wider areas of the planet. More than two-third of the earth's surface is covered with water. Water availability will remain constant in the near future. Most of the available water is either present as seawater or icebergs in the Polar Regions. About 97% of the earth's water is salty and rest is fresh water. Less than 1% fresh water is within human reach. Despite, technological progress, renewable fresh water reserves on earth will be only 0.3% of the world water. Agriculture uses two-third of available fresh water. The proportion of irrigated surface should increase by 1/3 in 2010 and by 50% in 2025. Industrial and domestic water use increases at twice the rate of population increase. Water consumption increased sevenfold since 1900. In total, water demand doubles every 20-year. Fresh water resources are almost completely exhausted in many middle-east countries [2].

It is estimated that the population will increase over the next 20 years (2000–2020) with about 50% in Africa, 25% in Asia, 14% in the USA and, surprisingly, 2% negative, in Europe. It is obvious that a considerable increase in the world population (over the next decade or so) will be concentrated mainly in most of the developing countries and particularly in Africa, causing severe water shortages [3]. As a result, 40% of the world population is struggling with serious water shortages, with the majority of this burden falling on people who live in remote rural areas and rapidly expanding urban areas [4].

The water emergency situation is certainly very alarming, especially in countries located within the southern Mediterranean belt also, the countries from southern Europe are partially affected by the lack of drinking water, and it is advisable to take appropriate actions to avoid serious negative impacts in the very near future.

World Water challenges for the 21st century are water scarcity, lack of accessibility, water quality deterioration, world peace and security, awareness by decision makers and the public, decline of financial resources allocation and fragmentation of water management.

Most of the water available on earth has the salinity up to 10,000 ppm whereas seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts. According to World Health Organization (WHO), the permissible limit of salinity in water is 500 ppm and for special cases goes up to 1000 ppm. Excess brackishness causes the problem of health. The annual water availability of 1000 m^3 per capita constitutes the limit below which it will not be possible to guarantee an acceptable living standard as well as economic development [5]. One of the control measures includes supply of water with total dissolved solids within permissible limits of 500 ppm or less. This is accomplished by several water desalination and purification methods.

Renewable energies are expected to have a flourishing future and an important role in the domain of brackish and seawater desalination in developing countries. Many industrial countries are already initiating a transition of their electricity supply schemes to higher renewable energy shares, by supporting market introduction and expansion of those technologies. The European Union has set a goal to double its renewable energy share until 2010, and the intergovernmental panel on climate change recommends a worldwide reduction of 75% of carbon emissions by the end of this century in order to avoid dangerous, uncontrolled effects on climate and on the world's economy.

The sustainable energy systems should take into consideration the environmental impact, technical, social and economical point of view. Solar thermal power generation is playing an important role in a well-balanced mix of renewable energy sources (RES), efficient power technologies and rational use of energy.

Throughout the world a trend to intensified use of desalination as a means to reduce current or future water scarcity can be observed. Water scarcity, which occurs not only in arid regions, may be characterized as a mismatch between water supply and water demand. Over a billion people worldwide lack access to sufficient water of good quality. Most of these people live in Asia and Africa. The growing population causes a steady rise in the living standards leads to increase the specific water consumption per capita.

The lack of potable water poses a big problem in remote and arid regions. Pollution and exploitation of groundwater aquifers and surface water have led to a decrease of quantity and/or quality of available natural water resources in many regions.

The dramatic increase in desalinated water supply will create a series of problems, the most significant of which are those related to energy consumption. It has been estimated that a production of 13 million m^3 of portable water per day requires 130 million tons of oil per year [6]. Given the current under-standing of the greenhouse effect and the importance of CO_2 levels, this use of oil is debatable. Thus, apart from satisfying the additional energy-demand, environmental pollution would be a major concern. CO_2 emissions can be greatly reduced through the application of renewable energy technologies, which are already cost competitive with fossil fuels in many situations.

If desalination is accomplished by conventional technology, then it will require the burning of substantial quantities of fossil fuels. Given that conventional sources of energy are polluting, sources of energy that are not polluting will have to be used. Fortunately, countries which lie in high solar insolation band and the vast solar potential can be exploited to convert saline water to potable water. Where the demand for fresh water exceeds the amount that fresh water sources can meet, desalination of lower quality water provides a reasonable new fresh water source. Desalination (desalting) of brackish water and seawater to provide the needed drinking water fulfills a basic social need and, in general, it does this without any serious impact on the environment. Nowadays, desalination has become a very affordable solution to cope with fresh water shortage typically in tropical as well as of off-shore areas.

Factors that have the largest effect on the cost of desalination are feed water quality (salinity levels), product water quality, energy costs as well as economies of scale [7,8].

Seawater desalination is being applied at 58% of installed capacity worldwide, followed by brackish water desalination accounting for 23% of installed capacity [9,10]. Fig. 1 outlines the global desalting capacity by feed water sources.

Since 1950, global water use has tripled and in the next 20 years, it is estimated that humans will require 40% more water

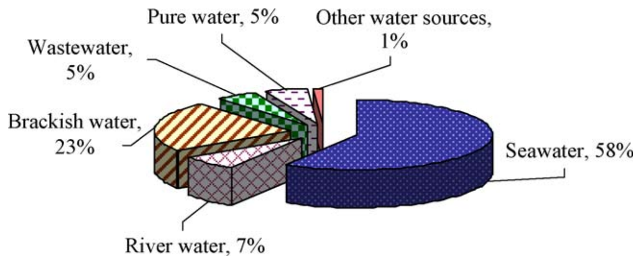


Fig. 1. Global installed desalination capacity by feed water sources [11].

than is currently being used [4]. Meanwhile, the existing supply of natural water resources is declining as a result of increasing water pollution (90% of wastewater in developing countries is released directly into rivers and streams without treatment) and over-exploitation of groundwater sources (groundwater currently supplies 50% of drinking water, 40% of industrial water and 20% of agricultural water globally) [12]. Finally, climate change may disrupt current rainfall patterns and regional water cycles around the globe.

The costs of water produced by desalination have dropped considerably over the years as a result of reductions in price of equipment, reductions in power consumption and advances in system design and operating experiences. As the conventional water supply tends to be more expensive due to over-exploitation of aquifers and increasing contaminated water resources, desalted water becomes a viable alternative water source.

Unprecedented commitment on a global scale to innovate new water technologies and management systems will be required to: (1) preserve the quality of our current supplies, (2) reduce the demand for water through gains in efficiency, and (3) increase the overall quantity of freshwater available.

This paper seeks to address the third intervention described above, by exploring the global potential for integrating renewable energy sources (RES) and desalination technologies aiming to light up their prospective characteristics and increase water supplies. Desalination processes are used to convert abundant salty water to relatively scarce freshwater and therefore represent great potential for water scarcity alleviation. The major limitation of desalination is its high energy requirements, and therefore it is useful to explore how RES can be linked into desalination systems for sustainable freshwater production into the future, considering the technological advancements and costs.

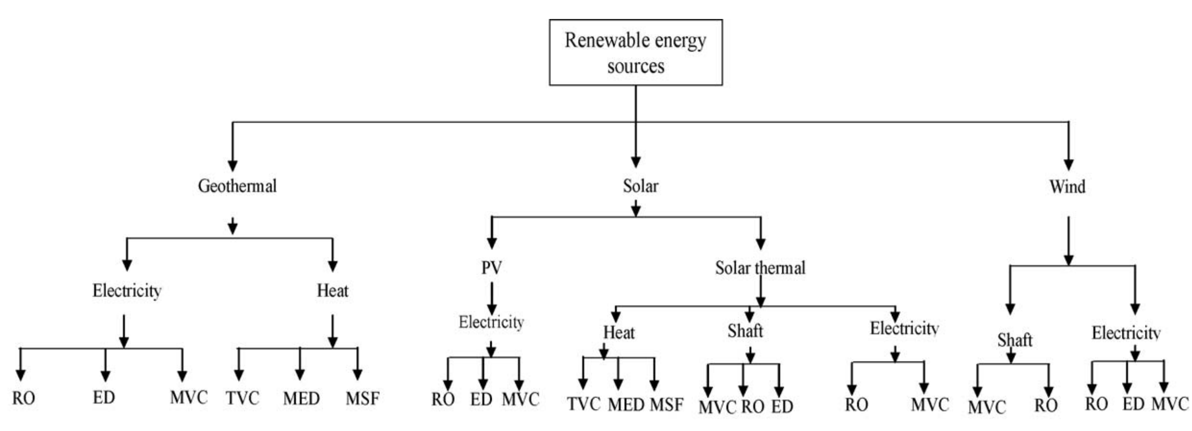
2. Renewable energy coupling to desalting technologies

Renewable energies for use in desalination processes include wind, solar thermal, photovoltaic and geothermal. Renewable energy driven desalination systems fall into two categories. The first category includes distillation processes driven by heat produced by the renewable energy systems, while the second includes membrane and distillation processes driven by electricity or mechanical energy produced by RES.

The most investigated mode of coupling between RES and desalination processes is the use of direct sun rays to produce fresh water by means of solar stills. Numerous attempts to harness solar thermal energy for water distillation have been carried out in many places worldwide [13,14]. Belessiotis and Delyannis [15], Delyannis and Belessiotis [16], Mathioulakis et al. [17] and Garcia-Rodriguez [6] presented valuable reviews of renewable energy systems. Also, there are other general reviews of renewable energy-powered desalination are, among others: Baltas et al. [18] Belessiotis and Delyannis [19], Garcia-Rodriguez [20], or Rodriguez-Girones et al. [21]. Voivontas et al. [22] developed software about alternative renewable-energy-powered desalination that includes costs analysis. Since solar desalination is one of the most promising technologies there are many reviews in the literature as follows: Delyannis [13], Delyannis and Belessiotis [16], or Garcia-Rodriguez and Gomez-Camacho [14]. Interesting comparisons of such system are given in El-Nashar [23], Kalogirou [24], Garcia-Rodriguez and Gomez Camacho [25]. While, the present status and economics of solar desalination are given in Al-Shammiri and Safar [26], Goosen et al. [27], Kamal et al. [28], Mohsen and Al-Jayyousi [29] and Rognoni and Trezzi [30].

Many studies have investigated the effect of different design parameters on the overall performance of solar stills, for example: Garg and Mann [31] Rajvanshi [32], Tiwari et al. [33,34], Zaki et al. [35], Al-Hussaini and Smith [36] and Singh et al. [37]. In this context, Tunisia has been a pioneer in exploring the possibility of water desalination through single basin solar stills. A number of desalination plants consisting of glass covered solar stills have been constructed in many parts of the country in the late 1960s [38].

Numerous attempts and experiments have been carried out throughout the world in an attempt to find suitable coupling procedures between desalination processes and RES. The suitability of a given renewable energy source for powering certain desalting processes depends on both the requirements of such processes and the form of energy that can be obtained from the considered source. Different plausible combinations between renewable energy sources and desalination technologies can be



PV= Photovoltaic, RO= Reverse osmosis, ED= Electrodialysis, MVC= Mechanical vapor compression, MED= Multi effect distillation, MSF= Multi stage flash distillation, TVC= Thermal vapor compression

Fig. 2. Combinations technologies of RES and desalination methods.

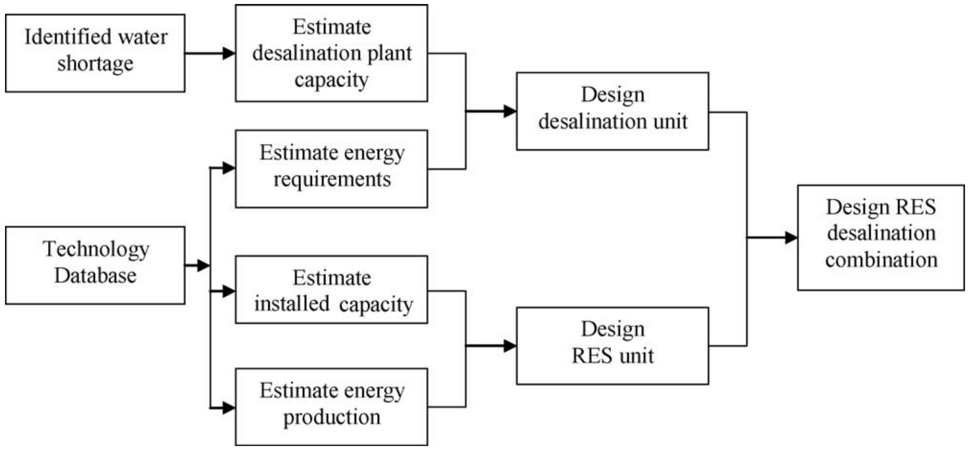


Fig. 3. Design of the appropriate RES/desalination plant.

envisaged [21]. The interface between the renewable energy system and the desalination system is met at the place/subsystem where the energy generated by the RE system is promoted to the desalination plant. This energy can be in different forms such as thermal energy, electricity or shaft power. Fig. 2 shows the possible combinations [12,39]. Fig. 3 presents the algorithm for the design of the appropriate RES/desalination plant [40].

Recently, there is a significant increase in efficiency and reduction of cost due to the intensive R&D efforts and operation experience gained, advances in conventional desalination plants, steam or electrically driven [41,42].

There are numerous renewable energy sources (RES)–desalination combinations have been identified and tested in the framework of ongoing research for innovative desalination processes [21,43–46]. Detailed assessments of available and exploitable water resources and water needs have been carried out in the framework of research programs [47–49] taking into account current and future trends of economic development and environmental and socioeconomic factors. Moreover, the market potential for RES desalination in specific regions has been identified, based on the combined evaluation of water shortage problems and RES potential with the objective to determine economically competitive options for RES-powered desalination [50,51].

Since there are many influential criteria for determining the best combination of RES and desalination technologies, there is a broad range of existing installations of RES desalination facilities. Fig. 4 shows the distribution of renewable energy powered desalination technologies [39].

Renewable energy represents the best energy supply option for autonomous desalination systems, especially in arid and coastal areas where the conventional energy supply is shortage. Self-sufficiency and local support can be achieved by both of renewable

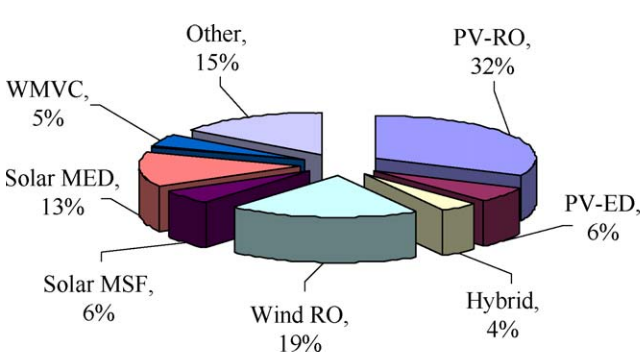


Fig. 4. Distribution of renewable energy powered desalination technologies.

energy systems and desalination. Climatic reasons lead to remarkable agreement on a time-basis, between the availability of RES, especially when referring to solar energy, and the intensive demand of water. The operation and maintenance of RES in remote areas are often easier than conventional energy ones. Renewable energies allow diversification of energy resources and help to avoid external dependence on energy supply. Seawater desalination processes are strongly energy consuming. Therefore, the environmental effects (Environmental impact) of the fossil fuels consumed are important. Note that total worldwide capacity of desalted water is about 23×10^6 m^3/d [52]. The cost reduction of renewable energy systems has been significant during the last decades. Therefore, future reductions as well as the rise of fossil fuel prices could make possible the competitiveness of seawater desalination driven by renewable energies.

Table 1 shows the relationship between various energy inputs and criteria for desalination technologies. While Table 2 shows the recommended renewable energy–desalination combinations.

In spite of the above mentioned advantages of RES which can be used to drive the desalination systems, but the current installed systems of RES–desalination are scarce and limited of about 0.02% of the total desalination capacity [53]. The reasons for this are related to various, often correlated, aspects such as:

(i) Availability, where the geographical distribution of RES potential does not always comply with the water stress intensity at a local level. (ii) Costs, where the initial capital instillation costs and various system components are still expensive. Even though prices decrease continuously still in many cases they are prohibiting for commercialization. (iii) Technologies, which imposes the combination of energy conversion and the desalination systems. A real challenge for these technologies would be the optimum technological design of combined plants which increase the efficiency as well as volume and decrease costs. (iv) Sustainability, where in most of the cases, the maturity of the associated technologies does not match the low level of infrastructures which often characterizes places with severe water stress. Experience has shown that several attempts to integrate advanced desalination solutions in isolated areas failed due to lack of reliable technical support [adapted from [17]]. Conversion of renewable energies, including solar, requires high investment cost and though the intensive R&D effort technology is not yet enough mature to be exploited through large-scale applications [17].

2.1. Selection of desalination-process

Renewable energies may be used in desalination processes and include wind, solar thermal, photovoltaic and geothermal.

Table 1
Evaluation of renewable energy technologies [53].

Criterion	Solar thermal energy	Photovoltaic	Wind energy	Geothermal energy
Suitability for powering desalination plants	Well suited for desalination plants requiring thermal power (3)	Well suited for desalination plants requiring electrical power (3)	Well suited for desalination plants requiring electrical power (3)	Well suited for desalination plants requiring thermal power (3)
Site requirements and resources availability	Typically good match with need for desalination (3)	Typically good match with need for desalination (3)	Resources is location-dependent (2)	Resources is limited to certain location (1)
Continuity of power output	Output is intermittent (energy storage required) (1)	Output is intermittent (energy storage required) (1)	Output is intermittent (energy storage required) (1)	Continuous power output (3)
Predictability of power output	Output is relatively unpredictable (2)	Output is relatively unpredictable (2)	Output is very unpredictable/ fluctuates (1)	Output is predictable (3)

Note: 3: excellent compliance with criterion; 2: good compliance with criterion; 1: poor compliance with criterion.

Matching renewable energies with desalination units, however, requires a number of important factors to be considered. Not all the combinations of RES-driven desalination systems are practicable, since many of these possible combinations may not be viable under certain circumstances. The optimum or just simple specific technology combination must be studied in connection to various local parameters as geographical conditions, topography of the site, capacity and type of energy available in low cost, availability of local infrastructures (including electricity grid), plant size and feed water salinity.

There are several factors to be considered for selecting desalination process suitable for a particular application, such as [adapted from [24]]:

i The amount of fresh water required in a particular application in combination with the range of applicability of the various desalination-processes.
ii The effectiveness of the process with respect to energy consumption.
iii Suitability of the process for solar-energy application.
iv The sea water treatment requirements.
v The capital cost of the equipment and imported material.
vi The land area required, or could be made available, for the installation of the equipment.
vii Robustness criteria and simplicity of operation,
viii Low maintenance, compact size and easy transportation to site.
ix Acceptance and support by the local community with minimum change to social sphere,
x Organization at local level with relatively simple training.

3. Desalination technologies

A desalting device essentially separates saline water into two streams: one with a low concentration of dissolved salts (the fresh water stream) and the other containing the remaining dissolved salts (the concentrate or brine stream). The device requires energy to operate and can use a number of different technologies for the separation. There are two basic technologies are utilized to remove the salts from ocean water: thermal distillation and membrane separation. Industrial desalination technologies use semipermeable membranes to separate the solvent or some solutes, or involve phase changes. All processes require a chemical pretreatment of raw brackish water to avoid scaling, foaming, corrosion, biological growth, and fouling and also it require a chemical post-treatment of the processed water. The categorization of desalination technologies are shown in Fig. 5.

Commercial desalination processes or conventional technologies to treat impaired or marginal quality waters consist of separating fresh water from saline water, simple settling, and disinfection with chlorine or iodine. This is including multi stage flash (MSF), multiple effect (ME), vapour compression (VC) which can be thermal (TVC) or mechanic (MVC), reverse osmosis (RO), ion exchange, electrodialysis, phase change and solvent extraction. These technologies are expensive especially for the production of small amount of fresh water. On the other hand, the use of conventional energy sources (hydrocarbon fuels) to drive these technologies has a negative impact on the environment. Several other membrane technologies are available for treatment of water to varying degrees. Those used in pre-treatment of desalination plants such as [54]:

- microfiltration (MF);
- ultrafiltration (UF); and
- nanofiltration (NF).

About 80% of the world's desalination capacity is provided by two technologies: Multi-stage flash (MSF), and reverse osmosis (RO). MSF units are widely used in the Middle East (particularly in

Table 2
Recommended renewable energy–desalination combinations [53].

Feed water available	Product water	RE resources available	System size			Suitable RE–desalination combination
			Small, 1–50 m^3/d	Medium, 50–250 m^3/d	Large, >250 m^3/d	
Brackish water	Desalinate	Solar	√			Solar distillation
	Potable	Solar	*			PV-RO
	Potable	Solar	*			PV-ED
	Potable	Wind	*	*		
	Potable	Wind	*	*		
Sea water	Desalinate	Solar	*			Solar distillation
	Desalinate	Solar		*	*	Solar thermal-MED
	Desalinate	Solar			*	Solar thermal-MSF
	Potable	Solar	*			PV-RO
	Potable	Solar	*			PV-ED
	Potable	Wind	*	*		Wind-RO
	Potable	Wind	*	*		Wind-ED
	Potable	Wind		*	*	Wind-VC
	Potable	Geothermal		*	*	Geothermal-MED
	Potable	Geothermal			*	Geothermal-MSF

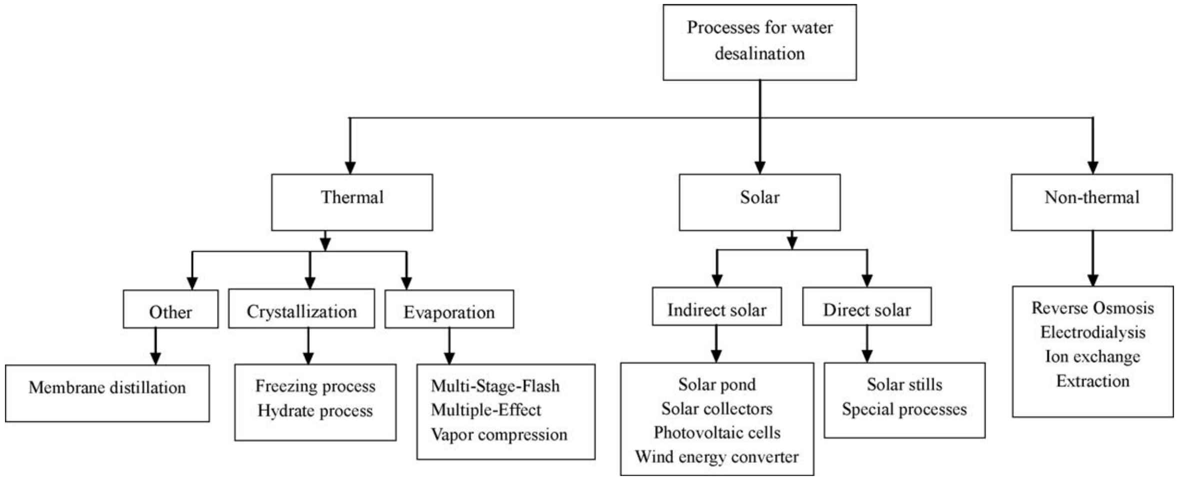


Fig. 5. Categories of desalination processes [adapted from [53]].

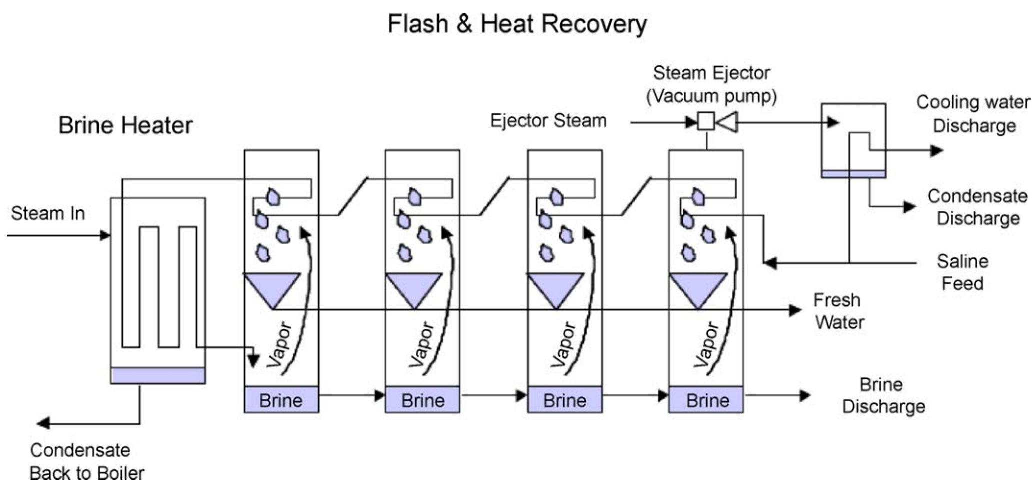


Fig. 6. Schematic diagram of a basic multi-stage flash (MSF) desalination process [56].

Saudi Arabia, the United Arab Emirates, and Kuwait) and they account for over 40% of the world's desalination capacity [55].

MSF and MED processes consist of a set of stages at successively decreasing temperature and pressure. MSF process is based on the generation of vapour from seawater or brine due to a sudden pressure reduction when seawater enters to an evacuated chamber. The process is repeated stage by stage at successively decreasing pressure (Fig. 6). This process requires an external steam supply, normally at temperature around 100 °C. The maximum temperature is limited by the salt concentration to avoid scaling and this maximum limits the performance of the process. A key design feature of MSF systems is bulk liquid boiling. This alleviates problems with scale formation on heat transfer tubes.

On MED, vapours are generated due to the absorption of thermal energy by the seawater. The steam generated in one stage or effect is able to heat the salt solution in the next stage because next stage is at lower temperature and pressure. The performance of the process is proportional to the number of stages or effects (Fig. 7). A MED plant normally uses an external steam supply at low temperature of about 70 °C. The low temperature MED is gaining more acceptances for low and medium capacity desalination plants, owing to following advantages:

- lower energy consumption;
- higher heat transfer coefficient;
- compactness;
- high product water quality; and
- reduced pre-treatment.

These newer LT-MED systems have also been studied in combination with solar energy input as small-scale desalination plants for remote areas [57].

On TVC and MVC, after initial vapour is generated from the saline solution, this vapour is thermally or mechanically compressed to generate additional production. Not only distillation processes involve phase change, but also freezing process. Fig. 8 provides a schematic illustration of the process. Low temperature VCD is a simple, reliable process and produces high quality product water (5–25 mg/L TDS). A number of desalination plants are installed worldwide for producing good quality water from saline water for industrial and municipal use. However, VCD plants have the disadvantage of restricted plant capacity due to scale limitations for large size vapour compressors [59]. Also, freezing desalination exhibits some technical problems which limit its industrial development.

On the other hand, other desalination processes do not involve phase changes. They are membrane processes, reverse osmosis (RO) and electrodialysis (ED)/electrodialysis reversal (EDR). It is forecast that membrane processes, and in particular RO, will continue to take market share from thermal desalination, with 59% of the total new build capacity being membrane based [60].

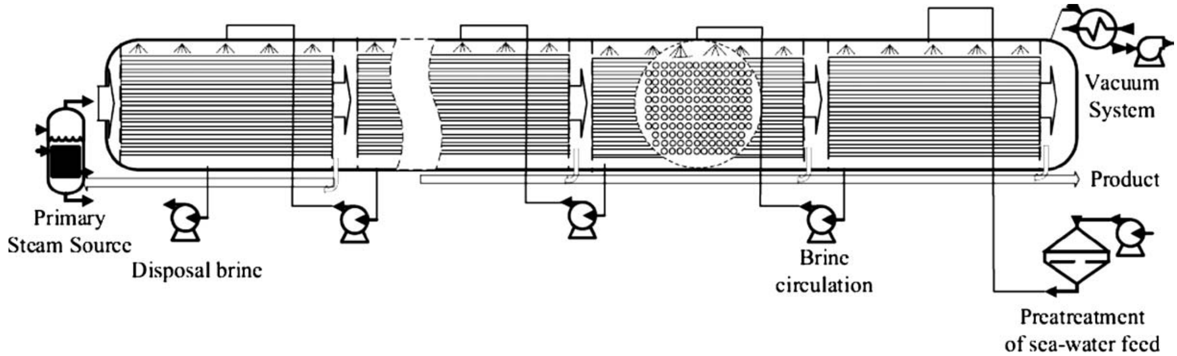


Fig. 7. Schematic presentation of horizontal tubes multi-effect distillation (MED) plant [58].

Both processes (RO and ED/EDR) require energy inputs to overcome the existing osmotic pressure between fresh water and saltwater. ED technology is usually limited to brackish feed water, while RO technologies can be used with brackish waters or seawater. Electrodialysis (ED) was developed about 10 years before RO and uses electric currents to draw salts through a selective membrane, leaving behind a freshwater effluent. Reverse Osmosis (RO) relies on forcing salt water against membranes (usually made of cellulose acetate or aromatic polyamide) at high pressure, so that water molecules can pass through membranes and the salts are left behind as a briny concentrate [61].

The dominant processes of MSF and RO are 44% and 42% of worldwide capacity, respectively. The MSF process represents more than 93% of the thermal process production, while RO process represents more than 88% of membrane processes production [6,56]. The schematic representations of these two types of membrane technologies (ED and RO) are shown in Figs. 9 and 10. Table 3 provides an overview of removal capabilities of each of membrane process. In water desalination, ED is competing directly with RO distillation and more recently NF.

The use of both renewable energy (i.e., solar and wind power) and desalination technologies are growing in absolute terms, as well as geographically. Meanwhile, the cost of implementing both of these technologies is decreasing. Additionally, the global population continues to grow, creating increased demand for both energy and water resources. Assuming all of these trends continue, it is likely that the integration of these two technologies will become an attractive option for increasing regional water supplies by producing freshwater from seawater.

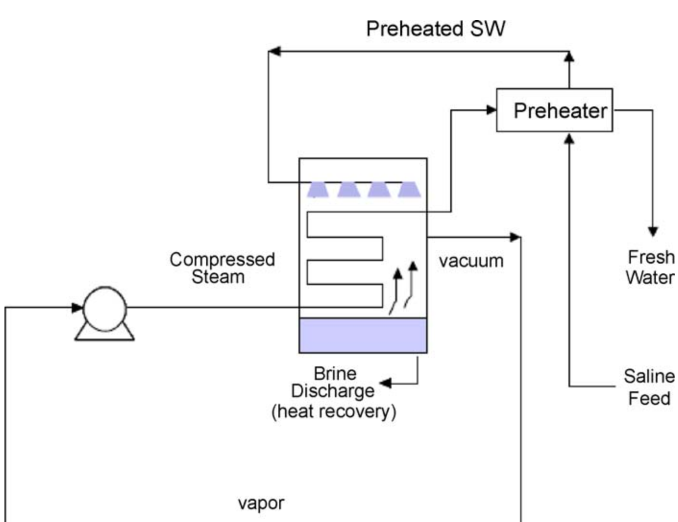


Fig. 8. Schematic diagram of a single stage mechanical vapour compression desalination process [56].

Energy requirement in the form of thermal as well as electrical energy can make up between 50% and 70% of the total operating cost and it is thus not surprising that many of the large-scale thermal desalination plants are co-located with power stations or industries with thermal process energy waste. The globally installed desalting capacity by process in 2002 is shown in Fig. 11.

The relative power requirements for the various types of desalination processes in the year 2000 are listed in Table 4. It is clear from the data presented in the table that thermal desalination processes require more total energy than RO processes per unit volume of water treated.

3.1. Solar still

Processes driven by solar energy generally fall into two categories, those that capture and utilize the thermal energy of the sun, and those that use photovoltaic (PV) devices to generate electricity. Solar stilts are used to produce the hydrological cycle on a much smaller scale by directly utilizing sunshine. Construction and operation principle of solar stills are simple. The basic design of a solar still, which is similar to a greenhouse, is shown in Fig. 12. Solar energy enters the device through a sloping clear glass or plastic panel and heats a basin of salt water. The basin is generally black to absorb energy more efficiently. The heated water evaporates and then condenses on the cooler glass panels. The condensed droplets run down the panels and are collected for use.

Solar stills typically are less than 50% efficient, e.g. they utilize less than 50% of the incident radiation [67]. A general rule of thumb is that about 1 m^2 of ground will produce only 4 L per day of freshwater [68]. Because of this, it is important to use very

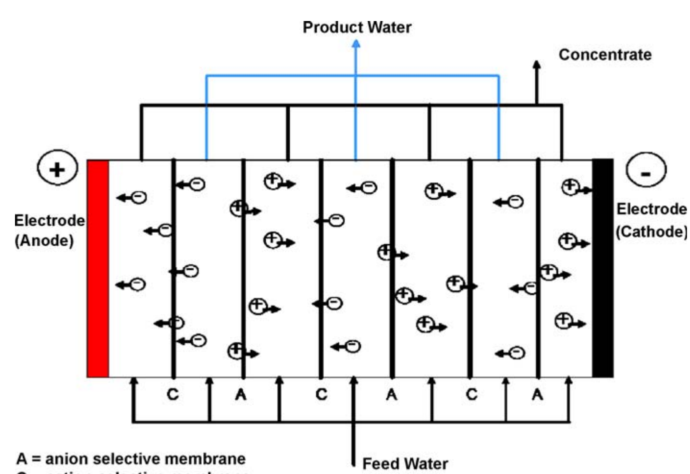


Fig. 9. Principle of electrodialysis under constant DC current field [54].

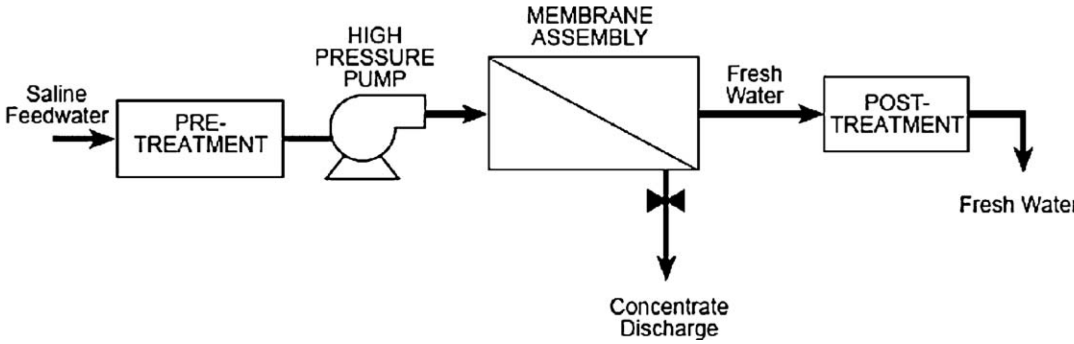


Fig. 10. Schematic of a simple reverse osmosis (RO) system [62].

inexpensive materials of construction to minimize capital costs. Even so, the installation costs of solar stills tend to be considerably higher than other methods [67]. In addition the stills are vulnerable to weather damage and they require large areas of land for installation and have low output. Modifications to the stills to increase efficiency, such as trackers to follow the sun, have generally proven to be too expensive to be practical. However, stationary stills tilted towards the sun do experience an incident energy increase of about 16%. The major energy loss from solar stills is low energy radiation from brine to the cover. Heat losses to the ground are small [67]. Research activities nowadays aim to strengthen the position of solar stills and to increase its water productivity, increase reliability and reduced initial cost. Such actions involve new designs of solar distillation systems that increase output through the increase of water temperature in the still. This can be achieved by heat recovery in multi-effect solar still or by coupling solar still with a heat storage tank, heated by any source nearby.

Therefore, solar stills represent the best technical solution to supply remote villages or settlements with fresh water without depending on high technology and expertise. A capillary film distiller called DIFICAP (distiller with a film in capillary motion) in which a very thin layer of tissue with fine mesh, saturated with water, is maintained in close contact with a metal plate due to the surface tension, which is much greater than the gravitational forces was devised by [69–73]. The different classifications of developments for single effect solar stills are presented in Fig. 13.

3.2. PV-driven RO and ED processes

There are mainly two PV driven membrane processes, reverse osmosis (RO) and electrodialysis (ED). Both techniques are described above, and from a technical point of view, PV as well as RO and ED are mature and commercially available technologies at present time. The feasibility of PV-powered RO or ED systems, as valid options for desalination at remote sites, has also been proven [75]. Indeed, there are commercially available standalone, PV powered desalination systems [76]. The main problem of these technologies is the high cost and, for the time being, the availability of PV cells. Many of the early PV-RO demonstration systems were essentially a standard RO system, which might have been designed for diesel or mains power, but powered from batteries that were charged by PV. This approach tends to require a rather large PV array for a given flow of product, due to poor efficiencies both in the standard RO systems and in the batteries. Large PV arrays and regular replacement of batteries would tend to make the cost of water from such systems rather high. Table 5 shows a selection of some brackish-water PV powered RO system.

Fig. 14 shows diagram of photovoltaic-powered reverse-osmosis (PV-RO) system to desalinate seawater without batteries. The system is operated from seawater and requires no batteries, since the rate of production of freshwater varies throughout the day according to the available solar power. Initial testing of the system, with the modest solar resource available in the UK, provided freshwater at approximately, 1.5 m^3/day. Nearer to the equator and with a PV array of only 2.4 kWp, a software model of the system predicts production of over 3 m^3/day throughout the year [85].

3.3. Concentrating solar thermal driven desalination

The concentrating solar technologies are used to convert the sun's energy into high-temperature heat. The heat energy is then used to generate electricity in a steam generator or any other purposes. Concentrating solar power's relatively low cost and ability to deliver power during periods of peak demand, i.e., it can be a major contributor to the nation's future needs for distributed sources of energy.

The main challenge of solar thermal power engineering and development is to concentrate solar energy which has a relatively low density. Therefore, mirrors with up to 95% reflectivity that continuously track the sun are required for this purpose. The concentrating solar technologies can be trough systems, dish/engine systems and power towers. A parabolic trough solar collector is designed to concentrate the sun's rays via parabolic curved solar reflectors onto a heat absorber element – a "receiver" – located in the optical focal line of the collector. The solar collectors track the sun continuously. The key components of a parabolic trough power plant are mirrors, receivers and turbine.

Table 3
Overview of typical particle removal achieved by membrane processes with application to potable water [63–65].

Process	Operating pressure (kPa)	Pore size (μm)	Approximate particle size removed
RO	1000–5000	≥0.0001	Metal ions (monovalent), aqueous salts
ED/EDR	–	–	Metal ions, aqueous salts
NF	500–1000	≥0.001	Metal ions (divalent) organic chemicals (humus), hardness, synthetic dyes, herbicides, pesticides, sugars, detergents, soaps, radionuclides, cysts, viruses
UF	30–50	≥0.01	Organic macromolecules, colloids, protein, gelatin, viruses
MF	30–50	≥0.1	Turbidity, clay, asbestos, algae, bacteria

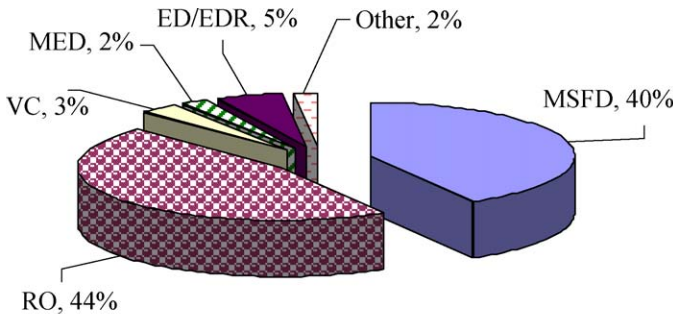


Fig. 11. Global installed desalting capacity by process [11].

In solar dish/engine systems, parabolic dishes capture the solar radiation and transfer it to a stirling engine – an engine which uses external heat sources to expand and contract a fluid – placed in the focus of the parabolic dish. This approach is particularly suited for decentralized electricity generation. Solar heat can be stored during the day in con Crete, ceramics or phase change media. At night, it can be extracted from the storage to run the power block. Fossil and renewable fuels like oil, gas and organic waste can be used for co-firing the plant, providing power by demand, as base or peak load (Fig. 15) [86].

The output per collector area is not a definitive guide to the best technology, as it does not take into account reliability and maintenance needs and relative capital costs. Neither has any detailed consideration been given to how the desalination plant could be run at a steady operating point; for example if the desalination is electrically driven how to the solar plant generating capacity would be sized so as to optimize the overall economics. The choice of the RO desalination plant capacity depends on the daily and seasonal variations in solar radiation levels, on the buying and selling prices for electricity, and on the weight given to fossil fuel displacement. A conceptual layout for a solar dish based system with power generation and RO desalination is shown in Fig. 16 [87].

The low temperature waste heat is shown as an input to the feed water as a reduction in RO energy consumption is achieved if the feed water temperature is raised (but only up to a limit which is determined by the membrane characteristics and other operating parameters). A modification of this arrangement is described in [88]: steam is used primarily to power a steam turbine and generate electricity, but is also extracted from the turbine (at reduced pressure and temperature) and used to drive a booster pump, which provides part of the RO high pressure pumping demand.

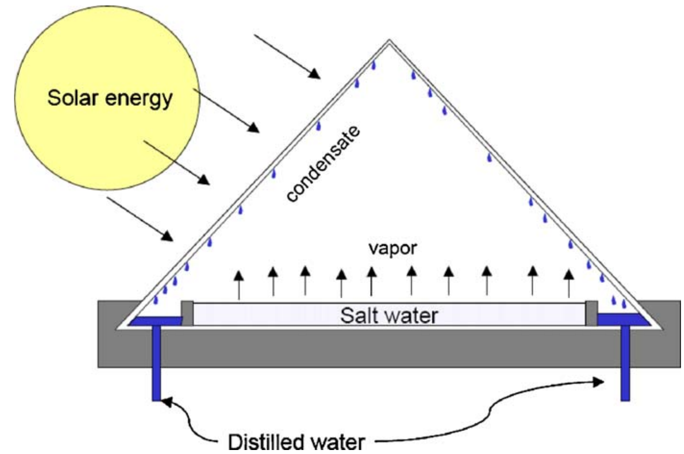


Fig. 12. The basic design of a solar distillation unit [66].

3.4. Wind driven water desalination

Remote areas with potential wind energy resources such as islands can employ wind energy systems to power seawater desalination for fresh water production. The advantage of such systems is a reduced water production cost compared to the costs of transporting the water to the islands or to using conventional fuels as power source. Different approaches for wind desalination systems are possible. First, both the wind turbines as well as the desalination system are connected to a grid system. In this case, the optimal sizes of the wind turbine system and the desalination system as well as avoided fuel costs are of interest. The second option is based on a more or less direct coupling of the wind turbine(s) and the desalination system. In this case, the desalination system is affected by power variations and interruptions

Table 4
Relative power requirements of desalination processes [66].

Process	Gain output ratio[a]	Electrical energy consumption (kWh/m^3)	Thermal energy consumption (kWh/m^3)	Total energy consumption (kWh/m^3)
MSF	8–12	3.25–3.75	6.75–9.75	10.5–13
MED	8–12	2.5–2.9	4.5–6.5	7.4–9
MED-TVC	8–14	2.0–2.5	6.5–12	9–14
MVC	N/A	9.5–17	N/A	9.5–17
BWRO[b]	N/A	1.0–2.5	N/A	1.0–2.5
SWRO[c]	N/A	4.5–8.5	N/A	4.5–8.5

[a] GOR: gain output ratio—the ratio of fresh water output (distillate) to steam.
[b] BWRO: Brackish water RO.
[c] SWRO: seawater RO.

Table 5
A selection of some brackish-water PV-RO systems.

Location	References	Feed water (ppm)	Capacity (m^3/d)	PV (kWp)	Batteries (kWh)
Sadous, Riyadh, Saudi Arabia	[77,78]	5800	15	10	264
Haifa, Israel	[79]	5000	3	3.5 plus 0.6 wind	36
Elhamrawien, Egypt	[80]	3500	53	18	200
Heelat ar Rakah, Oman	[81]	1000	5	3.25	9.6
White Cliffs, Australia	[82]	3500	0.5	0.34	NONE
Solarflow, Australia	[83] [84]	5000	0.4	0.12	NONE

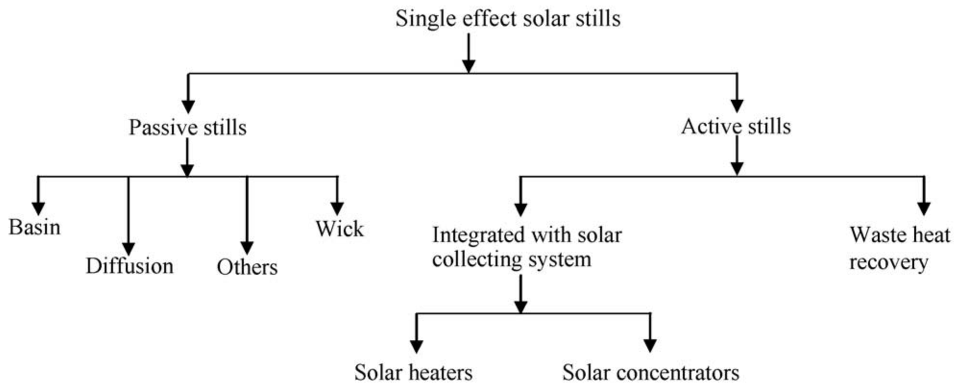


Fig. 13. Classifications of developments for single effect solar stills [adapted from [74]].

caused by the power source (wind). These power variations, however, have an adverse effect on the performance and component life of certain desalination equipment. Hence, back-up systems, such as batteries, diesel generators, or flywheels might be integrated into the system. Main research in this area is related to the analysis of the wind plant and the overall system performance as well as to developing appropriate control algorithms for the wind turbine(s) as well as for the overall system.

Regarding desalinations, there are different technologies options, e.g. electro-dialysis or vapour compression. However, reverse osmosis is the preferred technology due to the low specific energy consumption [89]. Fig. 17 shows a schematic presentation of an RO desalination plant. The process takes place in ambient temperature. The only electrical energy required is for pumping the water to a relatively high operating pressure. The use of special turbines may reclaim part of the energy. Operating pressures vary between 10 and 25 bars for brackish water and 50–80 bars for seawater. High pressure is needed to allow sufficient permeation at relatively high concentrations of the concentrating brine along the membrane axis located in the pressure vessel. Water conversion can go as high as 90.95% in the case of light brackish water, down to 35 to 50% recovery in the case of seawater. Low recovery is obtained especially in a relatively closed sea, like the Red Sea or the Persian Gulf [58].

The European Community, e.g. with the Joule III project, funded different research programs and demonstration projects of wind desalination systems on Greek and Spanish islands. For general information on wind desalination research, see [90–92].

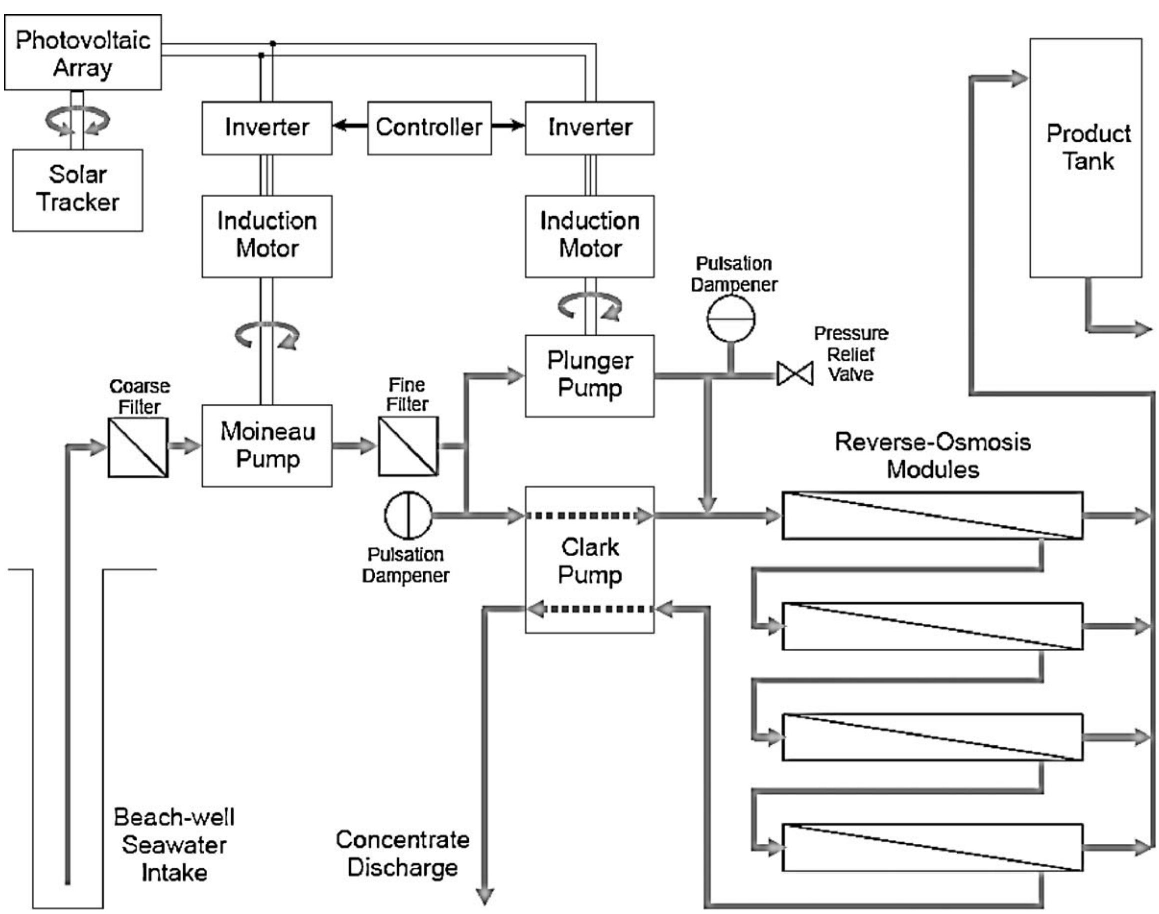


Fig. 14. PV-RO system to desalinate seawater without batteries [85].

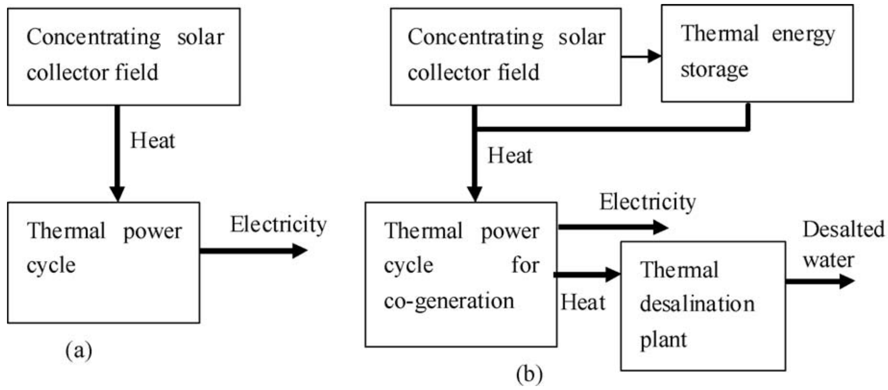


Fig. 15. Solar thermal power plant configuration for (a) electricity generation, and for (b) the combined generation of power and water with backup and energy storage.

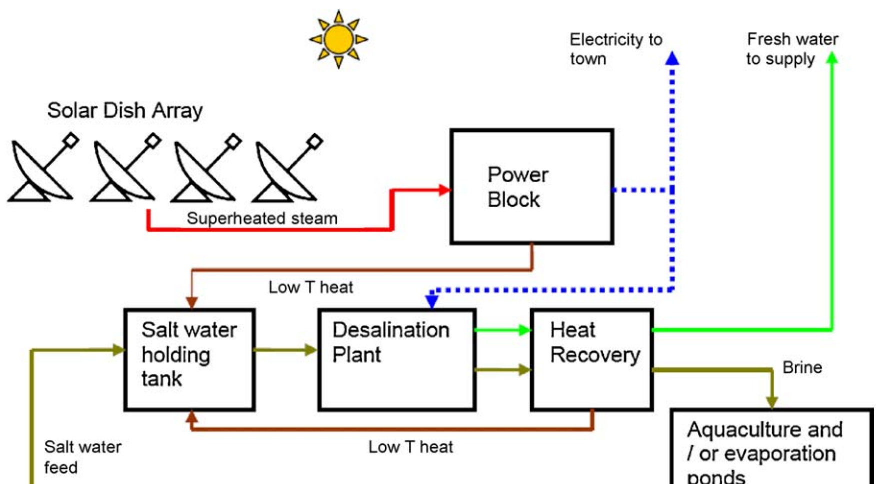


Fig. 16. Combined dish based solar thermal power generation and RO desalination.

For information on large stand-alone wind desalination systems, see [93,94]; for small systems, see [95]; and for an overview of the research activities in North America, see [96].

Other wind-driven RO systems are as follows: A RO system driven by a wind power plant, in Island of the County Split and Dalmatia, reported by [51]. The installation of RO in the Middle East was started in 1986. It is a 25 m^3/day-plant connected to a hybrid wind–diesel system [97]. Besides that, in Drepanon, Achaia, near Patras (Greece), in 1995 starts the operation of other wind powered RO system [98]. Finally, European Commission (1998) presents other facilities at:

- Island of Suderoog (North Sea), with 6–9 m^3/day;
- Ile du Planier, France Pacific Islands, with 0.5 m^3/h;
- Island of Helgoland, Germany (2.480 m^3/h);
- Island of St. Nicolas, West France (hybrid wind-diesel) and
- Island of Drenec, France (10 kW wind energy converter).

Interesting experimental research about the direct coupling of a wind energy system and a RO unit by means of shaft power has been carried out at the Canary Islands Technological Institute–– projects AERODESA I and AERODESA II [99]. In addition, in Coconut Island off the northern coast of Oahu, Hawai, a brackish water desalination wind-powered RO plant was analyzed. The system coupling directly the shaft power production of a windmill with the high pressure pump; 13 L/min can be maintained for wind speed of 5 m/s [100].

The ED process is interesting for brackish water desalination since it is able to adapt to changes of available wind power and it is most suitable for remote areas than RO. Modeling and experimental tests results of one of such system installed at the ITC, Gran Canaria, Spain is presented by [101]. The capacity range of this plant is 192–72 m^3/day.

3.5. Desalination powered by biomass and geothermal energy

The use of biomass in desalination is not in general a promising alternative since organic residues are not normally available in arid regions and growing of biomass requires more fresh water than it could generate in a desalination plant.

Also, even though geothermal energy is not as common in use as solar (PV or solar thermal collectors) or wind energy, it presents a mature technology which can be used to provide energy for desalination at a competitive cost. Furthermore, and comparatively to other RE technologies, the main advantage of geothermal energy is that the thermal storage is unnecessary, since it is both continuous and predictable [102].

The direct use of geothermal fluid of sufficiently high temperature in connection to thermal desalination technologies is the most interesting option [104]. The main advantage of geothermal energy comparing with other RES is that, the thermal storage is unnecessary, since it is both continuous and predictable [103]. A high-pressure geothermal source allows the direct use of shaft power on mechanically driven desalination, while high

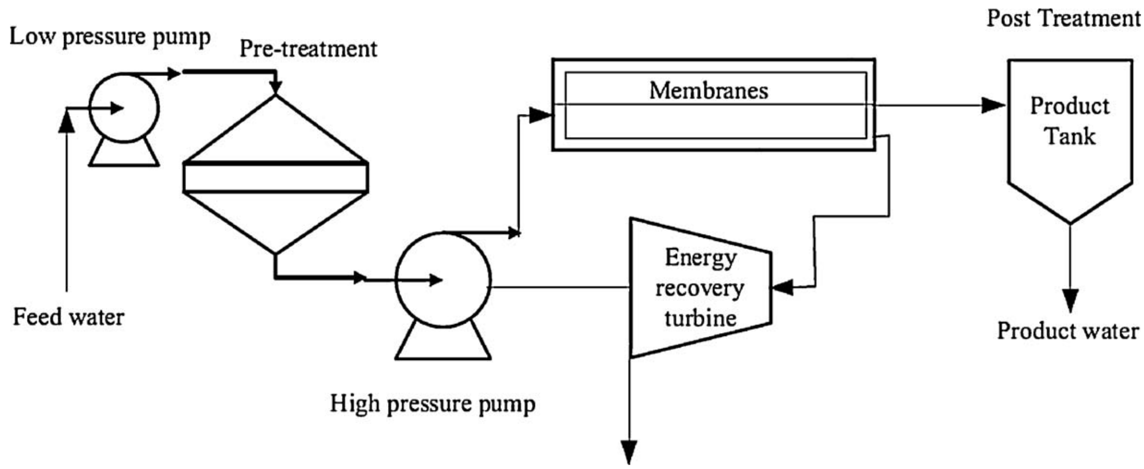


Fig. 17. Schematic presentation of a reverse osmosis desalination plant [58].

Table 6
Pros and cons of desalination processes [55].

Process	Recovery and Total dissolved solids	Pros	Cons
RO	30–60% recovery possible for single pass (higher recoveries are possible for multiple pass or waters with lower salinity)	Lower energy consumption	Higher costs for chemical and membrane replacement
		Relatively lower investment cost	Vulnerable to feed water quality changes
		No cooling water flow	Adequate pre-treatment a necessity
		Simple operation and fast start-up	Membranes susceptible to biofouling
		High space/production capacity	Mechanical failures due to high pressure operation possible
	<500 mg/L TDS for seawater possible and <less 200 mg/L TDS for brackish water	Removal of contaminants other than salts achieved	Appropriately trained and qualified personnel recommended
		Modular design	Minimum membrane life expectancy around 5–7 years
		Maintenance does not require entire plant to shutdown	
ED/EDR	85–94% recovery possible	Energy usage proportional to salts removed not volume treated	Only suitable for feed water up to 12,000 mg/L TDS
	140–600 mg/L TDS	Higher membrane life of 7–10 years	Periodic cleaning of membranes required
		Operational at low to moderate pressures	Leaks may occur in membrane stacks
			Bacterial contaminants not removed by system and post-treatment required for potable water use
MSF	25–50% recovery in high temperature recyclable MSF plant	Lends itself to large capacity designs	Large capital investment required
		Proven, reliable technology with long operating life	Energy intensive process
		Flashing rather than boiling reduces incidence of scaling	Larger footprint required (land and material)
	<50 mg/L TDS	Minimal pre-treatment of feed water required	Corrosion problems if materials of lesser quality used
		High quality product water	Slow start-up rates
		Plant process and cost independent of salinity level	Maintenance requires entire plant to shut-down
		Heat energy can be sourced by combining with power generation	High level of technical knowledge required
			Recovery ratio low
MED	0–65% recovery possible	Large economies of scale	High energy consumption
		Minimal pre-treatment of feed water required	High capital and operational cost
		Very reliable process with minimal requirements for operational staff	High quality materials required as process is susceptible to corrosion
	<10 mg/L TDS	Tolerates normal levels of suspended and biological matter	Product water requires cooling and blending prior to being used for potable water needs
		Heat energy can be sourced by combining with power generation	
		Very high quality product water	
VCD	~50% recovery	Developed process with low consumption of chemicals	Start-up require auxiliary heating source to generate vapour
	possible	economic with high salinity (>50,000 mg/L)	Limited to smaller sized plants
		Smaller economies of scale (up to 10,000 m^3/d)	Compressor needs higher levels of maintenance
	<10 mg/L TDS	Relatively low energy demand	
		Lower temperature requirements reduce potential of scale and corrosion	
		Lower capital and operating costs	
		Portable designs allow flexibility	

temperature geothermal fluids can be used to power electricity-driven RO or ED plants. The availability and/or suitability of geothermal energy, and other RE resources, for desalination, are given by [42].

4. Advantages and disadvantages of technologies

A comparative summary of the relative pros and cons identified for the desalination technologies as applied to seawater desalination is provided in Table 6. There are advantages and disadvantages when comparing membrane with thermal technologies and many factors need to be considered depending on the purpose and objectives for considering a particular desalination process. Advantages of membrane processes over thermal processes include [54]:

- lower capital cost and energy requirements;
- lower footprint and higher space/production ratio;
- higher recovery ratios;
- modularity allows for up- or downgrade and minimal interruption to operation when maintenance or membrane replacement is required;
- less vulnerable to corrosion and scaling due to ambient temperature operation; and
- membranes reject microbial contamination.

Advantages of thermal processes over membrane processes include:

- very proven and established technology;
- higher quality product water produced;
- less rigid monitoring than for membrane process required;
- less impacted by quality changes in feed water; and
- no membrane replacement costs.

5. The economics of desalination

Cost analysis of autonomous desalination system (ADS) usually aims to estimate the cost of a liter or a cubic meter of fresh water, and calculates the contribution of each cost item to the total cost. This identifies immediately the most significant cost items and attracts the attention to what should first be examined for possible improvement and cost reduction. In general, cost factors associated with implementing a desalination plant are site specific and depend on several variables. The cost estimation procedures are described in [104].

The major cost variables are: (i) quality of feedwater**,** where**,** the low TDS concentration in feedwater (e.g. brackish water) requires less energy for treatment compared to high TDS feedwater (seawater). (ii) Plant capacity where it affects the size of treatment units, pumping, water storage tank, and water distribution system. Large capacity plants require high initial capital investment compared to low capacity plants. But due to the economy of scale, the unit production cost for large capacity plants can be lower [105,106]. (iii) Site characteristics where it can affect water production cost such as availability of land and land condition, the proximity of plant location to water source and concentrate discharge point is another factor. Pumping cost and costs of pipe installation will be substantially reduced if the plant is located near the water source and if the plants concentrate is discharged to a nearby water body. (iv) Costs associated with water intake, pretreatment, and concentrate disposal can be substantially reduced if the plant is an expansion of an existing water treatment plant as compared to constructing a new plant. (v) Regulatory requirements which associated with meeting local/state permits and regulatory requirements [107]. It is difficult to compare the costs of desalination installations at an aggregated level because the actual costs depend on a range of variables specific to each site [108].

Desalination plant implementation costs can be categorized as construction costs (starting costs) and operation and maintenance (O & M) costs. Construction costs include direct and indirect capital costs. The direct cost includes land, production wells, surface water intake structure, process equipment, auxiliary equipment, buildings and concentrate disposal (type of desalination technology, plant capacity, discharge location, and environmental regulations). The indirect capital cost is usually estimated as percentages of the total direct capital cost. Indirect costs may include freight and insurance, construction overhead, owner's costs, and contingency costs.

The operating and maintenance (O & M) costs consist of fixed costs and variable costs. Fixed costs include insurance and amortization costs. Usually, insurance cost is estimated as 0.5% of the total capital cost. Typically, an amortization rate in the range of 5–10% is used. Major variable costs include the cost of labor, energy, chemicals, and maintenance. For low TDS brackish water, the replacement rate is about 5% per year. For high TDS seawater, the replacement could be as high as 20%. The cost for maintenance and spare parts is typically less than 2% of the total capital cost on an annual basis [107].

Table 7 shows the percent cost of various factors for desalination of brackish water and seawater in RO plants. These data are reported in the Sandia National Laboratories report compiling data from other sources [66].

It can be observed from these data, that:

(1) The fixed costs are a major factor for both, brackish water and seawater;
(2) The major difference in cost between desalination of brackish water and seawater is energy consumption, while the remaining factors are decreased proportionally, but remain about the same; and
(3) Costs associated with membrane replacement, maintenance & parts and consumables are relatively small. These costs depend on the status of technology and may be further reduced as technology evolves, but will not have significant impact on the overall cost of desalination.

Ghoneyem and Ileri [109] estimate that a production-size, solar still can produce water for $20/m^3 (1994 dollars), while Madani and Zaki [110] estimated solar distilled water production costs as low as $2.4/m^3. According to Bouchekima et al. [111], recent improvements in solar distillation technology make it the ideal technology for remote isolated areas with a water demand less than 50 m^3/d. All other technologies are more expensive at this small scale. Fath [112] believes solar stills are the technology of choice for water production needs up to 200 m^3/d. The dominant competing process is RO that has an energy requirement of between 22×10^6 and 36×10^6 J/m^3 (6 and 10 kWh/m^3) of water treated and investment costs of between US $600 and $2000/m^3 of production capacity [113]. The most commonly used solar distillation technology is a single effect, single-basin still characterized by a relatively large thermal mass, i.e., the water basin [114].

Table 7
Percent distribution of cost factors [66].

	Brackish water (%)	Seawater (%)
Fixed costs	54	37
Electric power	11	44
Labor	9	4
Membrane-replacement	7	5
Maintenance and parts	9	7
Consumables (chemicals)	10	3

Table 8
Unit product costs for conventional and novel desalination processes by capacity, plants operating in 2001 [116].

Type of system: capacity, in millions of gallons per day	Unit product cost, $ Cent/gallon
Novel processes	
MEE-VS, 30 effects, aluminum alloy, fluted tubes: 90.53	0.182
MEE-ABS, absorption heat pump and gas turbine: 2.5	0.133
Mechanical vapour compression (MVC)	
0.03	1.894
0.13	1.220
1.06	0.939
1.20	0.920
5.28	0.174
Reverse osmosis	
5.28 (single stage)	0.242
5.28 (two stage)	0.288
0.03	0.898
1.06	0.750
1.20	0.489
9.99	0.413
10.56	0.314
12.00	0.258
30.00	0.208
Multistage flash desalination (MSF)	
7.13 (dual-purpose)	0.292
7.13 (single-purpose)	0.621
8.45 (gas turbine, waste-heat boiler)	0.545
7.13	0.595
9.99	0.473
Multiple-effect evaporation (MEE)	
6 (dual-purpose)	0.330
6 (single-purpose)	0.739
6	0.529
6	0.470
9.99	0.409
9.99 (gas turbine, waste-heat boiler)	0.496
MEE-TVC	
5.85 (single-purpose)	0.886
5.85 (dual-purpose)	0.496
5.85	0.587

According to Loupasis [115], the RO technologies with energy recovery systems require the least amount of energy to process seawater (at 4–6 kWh/m^3) compared to all other technologies. If brackish water is included as a potential input, then the energy requirements for RO drop significantly and are basically equivalent to using ED treatment for brackish water (0.5–2.5 kWh/m^3).

Comparison of typical costs for seawater desalination by RO and typical thermal processes have shown that for RO the largest cost reduction potential lies in capital costs and energy (Fig. 18). For a typical large-scale thermal desalination plant, energy use represents 59% of the typical water costs with the other major expense being capital cost (Fig. 19). It would seem that the most effective cost reduction for thermal desalination can be achieved by utilising alternative sources of heat or energy, such as dual purpose plants. In addition, the development of less costly and corrosion-resistant heat transfer surfaces could reduce both capital and energy costs [108].

There is more detailed cost comparisons between the different desalination technologies are given in Table 8. Also Table 9 presents the comparison of renewable energy with fossil fuels and nuclear power. The data show that the costs of RO systems ranging from approximately 0.90 cents per gallon (US \$2.37/m^3) for a plant with capacity of .03 million gallons per day to 0.21 cents/gallon (US \$0.55/m^3) for a 30 m gallons/d capacity system.

Tables 10 and 11 show the desalination costs by all the power sources for 8% discount rate, with the average current prices for

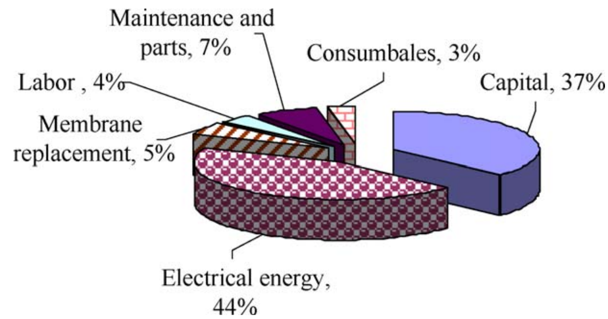


Fig. 18. Typical cost structure for RO desalination of seawater [108].

fossil fuels in the world markets. The figures in parentheses give the differences (in %) as compared to the desalination cost of the CFB-900 as reference, since it is the least expensive fossil fuelled option (without externalities) [118]. These differences are calculated for a given process as:

$$\Delta = 100 \times \left[\frac{\text{desalination cost (reactor-CFB-900)}}{\text{desalination cost CFB-900}}\right]$$

The above Tables lead to the following observations [118]:

- Because of rather low external values for nuclear systems, their power costs are least affected by the internalisation of environmental costs (5–10%).
- The power costs of fossil fuelled systems are strongly affected by the internalisation. The highest change is in coal fired plant in which the power costs are almost doubled and tripled when the external costs E_1 (lower limit of the external costs in France and/or Germany) and E_2 (upper limit of the external costs in France and/or Germany) are internalised.
- The coal based system, CFB-900, leads to the lowest power costs in normal conditions and with the internalisation of E_1. The tendency is reversed with E_2 for the CC-900 plant. The oil fired plant has the highest costs in all cases.
- The power costs of nuclear options are 24–45% lower than the power cost of the CFB-900 in normal conditions. They are 51–64% lower in E_1 scenario and 74–80% lower in E_2 scenario.
- The desalination costs are also influenced by these power cost differences although the corresponding decreases in the water costs are not directly proportional to the differences in power costs.
- Thus, compared to the CFB-900 + MED system, the desalination costs of the integrated MED plants with nuclear reactors are respectively 7–32% lower in normal conditions, 27–48% lower in the E_1 scenario and 52–65% lower in the E_2 scenario.
- The lowest costs with the MED plants are obtained by the GT-MHR and the PBMR, utilising virtually free waste heat. Compared to the cost by the CFB-900 + MED system, these reactors, coupled

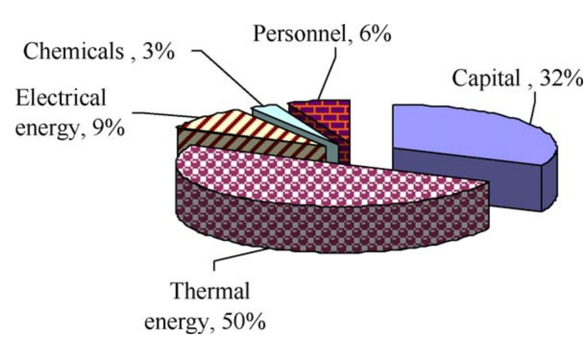


Fig. 19. Typical cost structure for large thermal desalination of seawater [108].

Table 9
Cost of renewable energy compared with fossil fuels and nuclear power [117].

Technology	Current cost (US cents/kWh)	Projected future costs beyond 2020 as the technology matures (US cents/kWh)
Biomass energy		
Electricity	5–15	4–10
Heat	1–5	1–5
Wind electricity		
Onshore	3–5	2–3
Offshore	6–10	2–5
Solar thermal electricity (insolation of 2500 kWh/m^2 per year)	12–18	4–10
Hydro-electricity		
Large scale	2–8	2–8
Small scale	4–10	3–10
Geothermal energy		
Electricity	2–10	1–8
Heat	0.5–5.0	0.5–5.0
Marine energy		
Tidal barrage (e.g. the proposed severn barrage)	12	12
Tidal stream	8–15	8–15
Wave	8–20	5–7
Grid connected photovoltaics, according to incident solar energy (insolation)		
1000 kWh/m^2 per year (e.g. UK)	50–80	~8
1500 kWh/m^2 per year (e.g. Southern Europe)	30–50	~5
2500 kWh/m^2 per year (most developing countries)	20–40	~4
Stand alone systems (incl. batteries), 2500 kWh/m^2 per year	40–60	~10
Nuclear power	4–6	3–5
Electricity grid supplies fossil fuels (incl. T&D)		
Off-peak	2–3	Capital costs will come down with technical progress, but many technologies already mature and may be offset by rising fuel costs
Peak	15–25	
Average	8–10	
Rural electrification	25–80	
Costs of central grid supplies, excl. transmission and distribution		
Natural gas	2–4	Capital costs will come down with technical progress, but many technologies already mature and may be offset by rising fuel costs
Coal	3–5	

to MED give desalination costs which are respectively 32% and 27% lower in normal conditions.
- Compared to the CFB-900 + RO system, the corresponding desalination costs by the PWR-900 + RO and AP-600 + RO are respectively 8.9% and 6.9% lower. In the E_1 scenario, these costs are 22% and 20% lower. The differences increase to 40–41% in the E_2 case.
- For all energy sources considered, the desalination costs with RO are 25–40% lower than those with MED.

RO remains the cheaper option at both low and high production capacities in comparison to the other technologies. However, it is important to restate that desalination cost data is extremely site specific, so the comparison of costs across the different technologies is not as straightforward as it may appear in the presented data.

Solar thermal power plants may acquire a considerable share on clean electricity generation in the 21st century. They are one of the best-suited technologies to achieve the global goals of CO_2 emission reduction. The energy payback time of a solar thermal power plant is in the order of 0.5 year, while the economic lifetime is at least 25 years [86].

Life cycle emissions of greenhouse gases amount to 0.010–0.015 kg/kWh, which is very low in comparison to those of gas fired combined cycles (0.500 kg/kWh) or steam/coal power plants (0.900 kg/kWh).

5.1. Decision support tool (DST)

To aid the process of cost calculation for a specific desalination technology and situation, a decision support tool (DST) software is

Table 10
MED water costs with/without externalities in France and Germany; 8% discount rate [118].

	CFB-900	CC-900	OIL-500	PWR-900	AP-600	GT-MHR	PBMR
Water costs ($/m3)	0.9487	1.3777	1.5713	0.84505	0.8795	0.6418	0.6942
Δ (%)		+45	+66	−10	−7	−32	−27
Water costs E_1 ($/m^3)	1.2378	1.4766	2.0581	0.86447	0.8989	0.6490	0.7021
Δ (%)		+19	+66	−30	−27	−48	−43
Water costs E_2 ($/m^3)	1.9147	1.7656	2.6361	0.87458	0.9090	0.6528	0.7062
Δ (%)		+7.8	+38	−54	−52	−65	−63

The nuclear power plants {four nuclear reactors: PWR-900, AP-600, GT-MHR and PBMR}. Three fossil fuelled power plants:{A 600 MWe circulating fluidized bed coal-fired plant (CFB-900), A 900 MWe gas turbine combined cycle plant (CC-900), and A 500 MWe oil-fired turbine (OIL-500)}.

Table 11
RO water costs with/without externalities in France and Germany; 8% discount rate [118].

	CFB-900	CC-900	OIL-500	PWR-900	AP-600
Water costs ($/m^3)	0.6928	0.8896	0.9539	0.63084	0.6451
Δ (%)		+28	+38	−8.9	−6.9
Water costs E_1 ($/m^3)	0.8140	0.93276	1.1581	0.63891	0.6532
Δ (%)		+14.6	+42	−22	−20
Water costs E_2 ($/m^3)	1.0979	1.05976	1.4005	0.6431	0.6574
Δ (%)		±3	+28	−41	−40

being developed within the ADIRA project, for detailed economic analysis of ADS systems [119]. For analysis, the DST authors [119] suggest to divide the cost of ADS into following categories as follows (Fig. 20):

i Cost of feed water system and pre-treatment, including all necessary investment and related expenses required for the supply of brackish or sea water to the desalination main system.
ii Cost of desalination unit itself.
iii Cost of supporting RE Source, supplying all the energy needs for the desalination unit, feed water pumps and brine disposal.
iv Cost of Brine water disposal, which could be anything from minimal to very expensive depending upon specific conditions.
v Other costs.

Most of the above categories have (a) an investment and (b) a running cost. The investment cot reflects the annual cost of purchasing and installing equipment or other fixed asset, while the running cost relates to annual expenses and the cost of various consumables which are necessary. The cost per litre or m^3 of fresh water is estimated by dividing the sum total annualised investment plus running costs of all categories by the volume of fresh water produced.

It should be noted, that for a given ADS technology, cost analysis is a site-specific and usually cannot be generalized for applications in other situations. As a general rule, the cost of the produced water by ADS is normally higher than conventional desalination technologies driven by network electricity or conventional fuel thermal energy. However in the remote areas far from electricity, fuel and fresh water resources as well as areas where the economic driven is tourism, the water price is acceptable. The developments currently underway suggest that ADS applications are going to become more wide spread.

An effective integration of desalination and renewable energy technologies will allow countries to address water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global problem of climate change. Meanwhile the costs of desalination and renewable energy systems are steadily decreasing, while fuel prices are rising and fuel supplies are decreasing. Finally, the desalination units powered by renewable energy systems are uniquely suited to provide water and electricity in remote areas where water and electricity infrastructure is currently lacking.

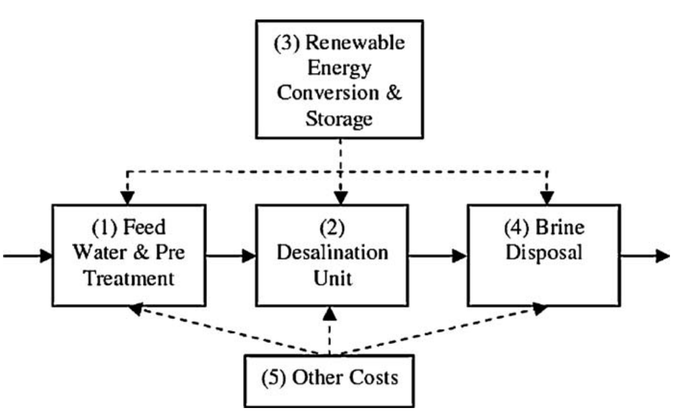


Fig. 20. DST cost categories [119].

6. Conclusions and outlook

The use of renewable energies for desalination appears nowadays as a reasonable and technically mature option towards the emerging and stressing energy and water problems. In spite of intensive research worldwide, the actual penetration of RES-powered desalination installations is still low. Recently there are intense attempt to develop and install effective large-scale desalination plants, mainly powered by RES. Practically, considerable skills and experience has been gained, even if this option appears to have entered a phase of relative stagnation. For low-density population areas worldwide there are lack of fresh water as well as electrical power grid connections. Therefore, the cheap fresh water may be produced from brackish, sea and oceans water by using wind turbines, solar panels and other emerging renewable energy technologies. The successful development of these technologies will be especially important for developing countries that are currently experiencing water scarcity and do not have access (geographically or economically) to sufficient conventional energy resources to implement desalination systems.

The connection of photovoltaic cells to membrane processes in desalination is an interesting alternative for stand-alone desalination systems in remote areas. Nevertheless, if wind power is available, it exhibit lower energy cost than solar PV energy. For brackish water desalination, both of them, RO and ED powered by wind turbines are usually the best selection. Nevertheless, solar distillation may be advantageous for seawater desalination, although other renewable energy resources have to be taken into account. Geothermal energy is suitable for different desalination process at reasonable cost wherever a proper geothermal source is available because there is no energy storage is required.

Moreover, other systems require further analysis for evaluating their potentials of development, applications and performance. The most mature technologies of renewable energy application in desalination are wind and PV-driven membrane processes and direct and indirect solar distillation. Nevertheless, the coupling of renewable energy and desalination systems has to be optimized. Also, the new pretreatments may improve the performance by permitting a considerable increase of the operating temperature in distillation plants. Environmental issues are associated with brine concentrate disposal, energy consumption and associated greenhouse gas production. On the other hand, social issues may include the public acceptance of using recycled water for domestic dual-pipe systems, industrial and agricultural purposes.

Acknowledgements

The investigation presented in this paper have been done in the frame of the development of the research project in the Department of Electrical Engineering, Tsinghua University, Beijing for postdoctoral program, which has been funded by the Tsinghua University.

References

[1] Fiorenza G, Sharma VK, Braccio G. Techno-economic evaluation of a solar powered water desalination plant. Energy Conversion and Management 2003;44:2217–40.
[2] http://www.sustainability.ca/index.cfm?body=chunkout.cfm&k1=403.
[3] Food and Agriculture Organization of the United Nations. The FAOSTAT database, population: annual time series. Rome: Food and Agriculture Organization of the United Nations; 2000.
[4] UNEP (United Nations Environment Programme). Key facts about water. 2003, http://www.unep.org/wed/2003/keyfacts, accessed January 15; 2006.
[5] World Health Organization. Guidelines for drinking water quality Recommendations, vol. I. Geneva: World Health Organization; 1984.
[6] Garcia-Rodriguez L. Renewable energy applications in desalination: state of the art. Solar Energy 2003;75:381–93.
[7] Alatiqi I, Ettouney H, El-Dessouky H. Process control in water desalination industry: an overview. Desalination 1999;126:15–32.
[8] Dore MHI. Forecasting the economic costs of desalination technology. Desalination 2005;172:207–14.
[9] Ebensperger U, Isley P. Review of the current state of desalination water policy working paper 2005-008. Georgia State University. Environmental policy program, Water Policy Centre; 2005.
[10] Schiffler M. Perspectives and challenges for desalination in the 21st century. Desalination 2004;165:1–9.
[11] IDA. IDA worldwide desalting inventory 2002. International Desalination Association; 2002.
[12] Edward S. The potential for wind-powered desalination in water-scarce countries. Master of Arts in Law and Diplomacy Thesis. February 7; 2006, http://fletcher.tufts.edu.
[13] Delyannis EE. Status of solar assisted desalination: a review. Desalination 1987;67:3–19.
[14] Garcia-Rodriguez L, Gomez-Camacho C. Perspectives of solar desalination. Desalination 2001;136:213–8.
[15] Belessiotis V, Delyannis EE. The story of renewable energies for water desalination. Desalination 2000;128:147–59.
[16] Delyannis EE, Belessiotis V. A historical overview of renewable energies. In: Mediterranean conference on renewable energy sources for water production. European Commission, EURORED Network, CRES, EDS; 1996. p. 13–7.
[17] Mathioulakis E, Belessiotis V, Delyannis E. Desalination by using alternative energy: review and state-of-the-art. Desalination 2007;203:346–65.
[18] Baltas P, Perrakis K, Tzen E. European network to integrate renewable energy into water production. In: Proceedings of Mediterranean conference on renewable energy sources for water production. European Commission, EURORED Network, CRES, EDS; 1996. p. 31–5.
[19] Belessiotis V, Delyannis EE. Water shortage and renewable energies (RE) desalination––possible technological applications. Desalination 2001;139: 133–8.
[20] Garcia-Rodriguez L. Seawater desalination driven by renewable energies: a review. Desalination 2002;143:103–13.
[21] Rodriguez-Girones, Rodriguez M, Perez J, Veza J. A systematic approach to desalination powered by solar, wind and geothermal energy sources. In: Proceedings of the Mediterranean conference on renewable energy sources for water production. European Commission, EURORED Network, CRES, EDS; 1996. p. 20–5.
[22] Voivontas D, Misirlis K, Manoli E, Arampatzis G, Assimacopoulos D, Zervos A. A tool for the design of desalination plants powered by renewable energies. Desalination 2001;133:175–98.
[23] El-Nashar AM. Optimizing the operating parameters of solar desalination plants. Solar Energy 1992;48:207–13.
[24] Kalogirou S. Use of parabolic trough solar energy collectors for sea-water desalination. Applied Energy 1998;60:65–88.
[25] Garcia-Rodriguez L, Gomez-Camacho C. Solar thermal technologies comparison for applications to seawater desalination. Desalination 2002;142(2): 135–42.
[26] Al-Shammiri M, Safar M. Multi-effect distillation plants: state of the art. Desalination 1999;126:45–59.
[27] Goosen MFA, Sablani SS, Shayya WH, Paton C, Al-Hinai H. Thermodynamic and economic considerations in solar desalination. Desalination 2000;129: 63–89.
[28] Kamal MR, Simandl J, Ayoub J. Cost comparison of water produced from solar powered distillation and solar stills. International Desalination and Water Reuse 1999;9(2):74–5.
[29] Mohsen MS, Al-Jayyousi OR. Brackish water desalination: an alternative for water supply enhancement in Jordan. Desalination 1999;124:163–74.
[30] Rognoni M, Trezzi A. Dissemination of small desalination plants limiting factors.In: Proceedings of the international workshop on desalination technologies for small and medium size plants with low environmental impact. Accademia Nazionale delle (1998). Renewable Energy 1999;14(1–4):275–80.
[31] Garg HP, Mann HS. Effect of climatic, operational and design parameters on the year round performance of single-sloped and double-sloped solar still under Indian arid zone conditions. Solar Energy 1976;18:159–63.
[32] Rajvanshi AK. Effect of various dyes on solar distillation. Solar Energy 1981;27:51–65.
[33] Tiwari GN, Minocha A, Sharma P, Khan M. Simulation of convective mass transfer in a solar distillation process. Energy Conversion and Management 1997;38:761–70.
[34] Tiwari GN, Mukherjee K, Ashok KR, Yadav YP. Comparison of various designs of solar stills. Desalination 1986;60:191–202.
[35] Zaki GM, Radhwan AM, Balbeid AO. Analysis of assisted coupled solar still. Solar Energy 1993;51:277–88.
[36] Al-Hussaini H, Smith IK. Enhancing of solar still productivity using vacuum technology. Energy Conversion and Management 1995;36:1047–51.
[37] Singh AK, Tiwari GN, Sharma PB, Khan E. Optimization of orientation for higher yield of solar still for given location. Energy Conversion and Management 1995;36:175–86.
[38] BenJemaa F, Houcine I, Chahbani MH. Desalination in Tunisia. Past experience and future prospects. Desalination 1998;116:123–34.
[39] Tzen E. Successful desalination RES plants worldwide. Hammamet, Tunisia: Centre for Renewable Energy Sources; 2005 , http://www.adu-res.org/pdf/CRES.pdf.
[40] Voivontas D, Yannopoulos K, Rados K, Zervos A, Assimacopoulos D. Market potential of renewable energy powered desalination systems in Greece. Desalination 1999;121:159–72.
[41] Leitner GF. Breaking the cost barrier for seawater desalting. International Desalination and Water Reuse Quarterly 1998;8(1):15–20.
[42] MEDRC R&D Report. Matching renewable energy with desalination plants, IT Power Ltd.; 2001.
[43] Joule-Thermie Programme. Desalination guide using renewable energies. European Commission; 1998.
[44] Hanafi A. Desalination using renewable energy sources. Desalination 1994;97(1–3):339–52.
[45] Rheinlander J, Lippke F, Schmitz-Goeb M, Tusel GF. Electricity and potable water from a solar tower power plant. Renewable Energy 1998;14(l–4):23–8.
[46] Caruso G, Naviglio A. A desalination plant using solar heat as a heat supply, not affecting the environment with chemicals. Desalination 1999;122:225–34.
[47] REDES. Decision support system for the integration of renewable energies into water desalination systems. Final report, EEC, DG XII, APAS RENA CT94-0058; 1996.
[48] PRODESAL. Towards the large scale development of decentralized water desalination. Final report, EEC, DG XII, APAS RENA CT94-0005; 1996.
[49] MEDCODESAL. Mediterranean cooperation for water desalination policies in the perspective of sustainable development. Task 2. Interim report, EEC, DG XII, INCO; 1999.
[50] Ben Jemaa F, Houcine I, Chahbani MH. Potential of renewable energy development for water desalination in Tunisia. Renewable Energy 1999;18:331–47.
[51] Vujcic R, Kmeta M. Wind-driven seawater desalination plant for agricultural development on the islands of the County of Split and Dalmatia. Renewable Energy 2000;19:173–83.
[52] El-Dessouky HT, Ettouney HM, Mandani F. International workshop for small and medium size plants with limited environmental impact Rome, 1998. Academia Nazionale delle Scienze detta Dei XL 1999;281–312.
[53] Delyannis E, Belessiotis V. A historical overview of renewable energies. In: Proc. Mediterranean conference on renewable energy sources for water production, EURORED network, CRES, EDS; 1996. p. 13–7.
[54] ASIRC (Australian Sustainable Industry Research Centre Ltd.). Overview of treatment processes for the production of fit for purpose water: desalination and membrane technologies report no.: R05-2207. July 25; 2005.
[55] Ettouney HM, El-Dessouky HT, Alatiqi I. Chemical Engineering Progress. September; 1999:43.
[56] Evans LR, Miller JE. Sweeping gas membrane desalination using commercial hydrophobic hollow fiber membranes. SAND report. SAND 2002-0138, Unlimited Release, Printed January; 2002.
[57] El-Nashar AM. The economic feasibility of small solar MED seawater desalination plants for remote arid areas. Desalination 2001;134:173–86.
[58] International Water Resources Association, Water International. Semiat R. Desalination, vol. 25, no. 1. International Water Resources Association, Water International; March 2000. p. 54–65.
[59] IAEA (International Atomic Energy Agency). Introduction of nuclear desalination; a guidebook. Technical report series no. 400. Vienna Austria; 2000.
[60] GWIP. Desalination markets 2005–2015: a global assessment and forecast. Global Water Intelligence Publication; 2004.
[61] Oldach R. Matching renewable energy with desalination plants (Muscat, Sultanate of Oman: The Middle East Desalination Research Center, MEDRC), MEDRC Series of R&D Reports, MEDRC Project: 97-AS-006a. September; 2001.
[62] Buros OK. The ABCs of desalting. Topsfield, MA: International Desalination Association; 2000, http://www.idadesal.org/ABCs1.pdf, accessed November 29; 2005.
[63] WHO, Water Treatment and Pathogen Control: Process Efficiency in Achieving Safe Drinking Water. World Health Organisation (LeChevallier MW, Au, K -K); 2004.

[64] Duranceau SJ, Henthorne LR. Membrane pre-treatment for seawater reverse osmosis desalination. Florida Water Resources Journal November 2004;33–7.
[65] Water Corporation. A strategic review of desalination possibilities for Western Australia. September; 2000.
[66] Miller JE. Review of water resources and desalination technologies. Albuquerque, NM: Sandia National Laboratories; 2004, 49 pp., http://www.sandia.gov/water/docs/MillerSAND2003_0800.pdf.
[67] Spiegler KS, El-Sayed YM. A desalination primer. Santa Maria Imbaro, Italy: Balaban Desalination Publications; 1994.
[68] Buros OK. The ABCs of desalting, second ed., Topsfield, MA: International Desalination Association; 2000.
[69] Kumar S, Tiwari GN. Performance evaluation of an active solar distillation system. Energy 1996;21:805–8.
[70] Lawrence SA, Tiwari GN. Theoretical evaluation of solar distillation under natural circulation with heat exchanger. Energy Conversion and Management 1990;30:205–13.
[71] Yadav YP, Jha LK. A double-basin solar still coupled to collector and operating in the thermosiphon mode. Solar Energy 1989;14:653–9.
[72] Soliman HS. Solar still coupled with solar heater. Mosul, Iraq: Mosul University; 1976. p. 43.
[73] Zaki GM, Radhwan AM, Balbeid AO. Analysis of assisted coupled solar stills. Solar Energy 1993;51(4):277.
[74] Fath HES. Solar distillation: a promising alternative for water provision with free energy, simple technology and a clean environment. Desalination 1998;116:45–56.
[75] MEDRC R&D Report, VARI-RO Solar Powered Desalting Study. SAIC, USA; 2000.
[76] Espino T, Peñate B, Piernavieja G, Herold D, Neskakis A. Optimised desalination of seawater by a PV powered reverse osmosis plant for a decentralised coastal water supply. Desalination 2003;156:349–50.
[77] Saleh A, Smiai MS, Rafique S, Stafford B. PV powered water pumping and desalination plant for remote areas in Saudi Arabia. Applied Energy 1995;52(2-3):283–9.
[78] Hasnain SM, Saleh AA. Coupling of PV-powered RO brackish water desalination plant with solar stills. Desalination 1998;116(1):57–64.
[79] Dan W, Fisher D, Moses EJ, Katz B, Meron G. Operation experience of a solar- and wind-powered desalination demonstration plant. Desalination 2001;137 (1–3):7–13.
[80] http://www.nrea.gov.eg/pv.htm, accessed September; 2007.
[81] Al Suleimani Z, Rajendran NV. Desalination by solar-powered reverse osmosis in a remote area of the Sultanate of Oman. Applied Energy 2000;65 (1–4):367–80.
[82] Richards BS, Schafer AI. Photovoltaic-powered desalination system for remote Australian communities. Renewable Energy 2003;28(13):2013–22.
[83] Kuruvilla M, Dallas S, Ho G, Anda M. Innovative solar-powered village potable water supply. Women Leaders on the Uptake of Renewable Energy Seminar. Perth, Australia, June; 2001. Also available at: http://acre.murdoch.edu.au/unep/papers/Mathew.pdf, accessed September; 2007.
[84] Maslin A, Annandale D, Saupin M. Decentralised water solutions Island infrastructure project. In: Proceedings of renewable energy sources for islands, tourism and water desalination conference, EREC (European Renewable Energy Council); 2003. p. 287–94.
[85] Thomson AM. Reverse-osmosis desalination of seawater powered by photovoltaics without batteries. PhD thesis. Loughborough University, June 30; 2003.
[86] Trieb F, Nitsch J, Kronshage S, Schillings C, Brischke LA, Kniesb G, et al. Combined solar power and desalination plants for the Mediterranean region—sustainable energy supply using large-scale solar thermal power plants. Desalination 2002;153:39–46.
[87] Burgess G, Lovegrove K. Solar thermal powered desalination: membrane versus distillation technologies. Canberra ACT, Australia: Centre for Sustainable Energy Systems Department of Engineering, Australian National University; 2000.
[88] Rostek Associates Inc. & US Dept of the Interior Bureau of Reclamation. Desalting Handbook for Planners, 3rd ed., Rostek Associates, Inc. & US Dept of the Interior Bureau of Reclamation; 2003.
[89] Ackermann T, Soder L. An overview of wind energy-status 2002. Renewable and Sustainable Energy Reviews 2002;6:67–128.
[90] Rodriguez-Girones, R J, Rodriguez Ruiz M, Veza J M. *Experience on desalination with renewable energy sources, work package 1, EURORED*, 194 APAS RENA-CT94-0063, Universidad de Las Palmas De Gran Canaria, March 1996.
[91] Desalination guide using renewable energies. Pikermi-Attiki, Greece: Maxibrochure under THERMIEDG XVII published by C.R.E.S. Centre for Renewable Energy Sources; 1998.
[92] Feron P. Use of wind power in autonomous reverse osmosis seawater desalination. Wind Engineering 1985;9(3):180–99.
[93] Rahal Z, Infield DG. Wind powered stand alone desalination. In: Proceedings of the European Wind Energy Conference; 1997. also available at: http://info.lboro.ac.uk/departments/el/research/crest/publictn.html.
[94] Rahal Z, Infield DG. Computer modelling of a large scale stand alone wind-powered desalination plant. In: Proceedings of the British Wind Energy Conference; 1997. also available at: http://info.lboro.ac.uk/departments/el/research/crest/publictn.html.
[95] Infield D. Performance analysis of a small wind powered reverse osmosis plant. Solar Energy 1997;61(6):415–21.
[96] Manwell JF, McGowan JG. Recent renewable energy driven desalination system research and development in North America. Desalination 1994;94(3):229–41.
[97] Stahl M. Small wind powered RO seawater desalination plant design, erection and operation experience. Seminar on new technologies for the use of renewable energies in water desalination. Commission of the European Communities, DG XVII for Energy, CRES (Centre for Renewable Energy Sources) Athens, 26–28 September; 1991.
[98] Kostopoulos C.In: Proceedings of the Mediterranean Conference on Renewable Energy Sources for Water Production; 1996. p. 20–5.
[99] ITC (Canary Islands Technological Institute). Memoria de gesti_on; 2001 [in Spanish].
[100] Lui CCK, Park JW, Migita R, Qin G. Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control. Desalination 2002;150:277–87.
[101] Veza J, Penate B, Castellano F. Electrodialysis desalination designed for wind energy (on-grid test). Desalination 2001;141:53–61.
[102] Barbier E. Geothermal energy technology and current status: an overview Renewable Sustain. Energy Review 2002;6:3–65.
[103] Belessiotis V, Delyannis E. Renewable energy resources, in Encyclopedia of Life Support Systems (EOLSS), desalination: desalination with renewable energies, available on line: http://www.desware.net/DeswareLogin/Login-Form.aspx.
[104] Cost Estimating Procedures. In: Desalting handbook for planners (Chapter 9). United States Department of Interior, Bureau of Reclamation, Technical Service Center, Desalination and Water Purification Research and Development Program Report No. 72 (3rd ed.) 2003: p. 187–231.
[105] LBG-Guyton Associates. Brackish groundwater manual for Texas Regional Water Planning Groups. Prepared for Texas Water Development Board; 2003: 31 pp.
[106] Younos T. The feasibility of using desalination to supplement drinking water supplies in Eastern Virginia.VWRRC Special Report SR25-2004. Blacksburg, VA: Virginia Water Resources Research Center, Virginia Tech; 2004: 114 pp.
[107] Younos T. The economics of desalination Universities Council on Water Resources. Journal of Contemporary Water Research & Education 2005;(December (132)):39–45.
[108] NRC review of the desalination and water purification technology roadmap. Washington DC; National Research Council/The National Academies Press, 2001.
[109] Ghoneyem A, Ileri A. Software to analyze stills and an experimental study on the effects of the cover. Desalination 1997;114:37–44.
[110] Madani AA, Zaki GM. Yield of stills with porous basins. Applied Energy 1995;52:273–81.
[111] Bouchekima B, Gros B, Oahes R, Diboun M. Performance study of the capillary film solar distiller. Desalination 1998;116:185–92.
[112] Fath HES. High performance of a simple design, two effects, solar distillation unit. Energy Conversion and Management 1997;38:1895–905.
[113] Komgold E, Korin E, Ladizhensky I. Water desalination by pervaporation with hollow fiber membranes. Desalination 1996;107:121–9.
[114] Aboabboud MM, Horvath L, Mink G, Yasin M, Kudish AI. An energy saving atmospheric evaporator utilizing low grade thermal or waste energy. Energy 1996;21(12):1107–17.
[115] Loupasis S. Technical analysis of existing RES desalination schemes (Commission of the European Communities Directorate-General for Energy and Transport, Altener Programme, Renewable Energy Driven Desalination Systems – REDDES, Contract number 4.1030/Z/01-081/2001) 2002.
[116] Ebensperger U, Isley P. Review of the current state of desalination: water policy working paper 2005-008. Georgia Water Planning and Policy Center; 2005, http://www.h2opolicycenter.org/wp2005.shtml, accessed Septtember 15; 2007.
[117] REN21 renewable energy policy network renewables 2005 global status report. Washington, DC: Worldwatch Institute; 2005.
[118] Nisan S, Benzarti N. A comprehensive economic evaluation of integrated desalination systems, using fossil fuelled and nuclear energies, and including their environmental costs. Desalination 2008;229(1–3):125–45.
[119] Soldatos PG, Assimakis D. Autonomous desalination systems (ADS) sizing and cost analysis: methodology, ADIRA document under preparation. Greece: AUA; 2007.